VALIDATION OF A SIMULATION PROCESS FOR ASSESSING THE RESPONSE OF A VEHICLE AND ITS OCCUPANTS TO AN EXPLOSIVE THREAT

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ABSTRACT

Lighter weight military vehicles facilitate faster transport, higher mobility, fuel conservation, and a reduced ground footprint of supporting forces. At the same time the design of ground combat vehicles to survive a blast from a mine or from any other explosive threats is of great interest in order to provide an appropriate level of protection for the vehicle and its occupants. Weight reduction and high levels of survivability are mutually competing objectives. Therefore, a significant effort must be invested in order to ensure that the vehicle's survivability is not compromised.

Full size blast tests are expensive and time consuming to organize. Using a numerical simulation for predicting the interaction of the blast load with the vehicle and the effects of the explosion to the occupants' safety can minimize the number of such trials, and it will identify the design changes which will increase the survivability of the vehicle and the crew. Such simulation capability must be physics based and able to account for non-centerline explosive threats; the load applied on the vehicle from the blast pressure and the high velocity projectiles (which can be part of the explosive threat); the interaction between the explosive threat, the vehicle, and the occupant; the soil/structure interaction and the gross vehicle response; and the effects of blast mitigation material, restraint system, and seat design to the loads developed on the members of an occupant.

A Blast Event Simulation sysTem (BEST) has been developed for facilitating the easy use of the LS-DYNA solvers for conducting a complete sequence of explosive simulations. An Anthropometric Test Device (ATD) can also be included in the simulations for assessing loads developed on an occupant during an explosion. The main technical capabilities embedded in the BEST simulation process along with comparisons between simulation results and test data available in the literature are presented in this paper. Details from a validation study associated with the response of a generic structure and a ADT placed inside the structure to the loads from an explosion are also discussed.

1. INTRODUCTION

The design of vehicles to resist a blast and provide protection to the vehicle and its occupants is of great interest. New combat vehicle designs emphasize weight reduction for increased fuel efficiency and airborne transportation; therefore, a significant effort must be invested to ensure that the vehicle's survivability is not compromised. Currently combat vehicles are subjected to blasts from explosive threats. The recent wars in Iraq and Afghanistan have underlined the importance for increasing the protection of a vehicle's occupant to explosions. In addition to the loss of life, either traumatic brain injuries or extremities injuries have been observed [Fischer, 2009; Galarneau et al, 2006].

In the past, several efforts have been made for modeling explosions and their effect on structures [Gupta, 1999; Bird, 2001; Gupta, 2002; Sun et al, 2006]. Empirical loading models have also been developed for predicting the effects of blast mines on structures. Empirical blast loading functions were implemented in the CONWEP code [Kingery and Bulmarsh, 1984] for modeling the free air detonation of a spherical charge. Another empirical relationship was developed for predicting the impulse applied by a buried mine to a plate at a given offset from the mine [Westine et al, 1985]. Both empirical models were integrated with the LS-DYNA commercial code. The CTH hydrocode [McGlaun et al, 1990; Bell and Hertel, 1994] has been developed by Sandia National Laboratories and utilized for blast event simulations in multiple occasions [Gupta, 1999; Gupta, 2002; Gupta et al, 1987; Gupta et al 1989, Joachin et al, 1999] for modeling blast events.

In this paper the Eulerian solver of LS-DYNA is employed for simulating the soil – explosive – air interaction and calculating accurately the loads on a target structure. Sequentially, the LS-DYNA Langragian solver is used for computing the corresponding response of a

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14. ABSTRACT
Lighter weight military vehicles facilitate faster transport, higher mobility, fuel conservation, and a reduced ground footprint of supporting forces. At the same time the design of ground combat vehicles to survive a blast from a mine or from any other explosive threats is of great interest in order to provide an appropriate level of protection for the vehicle and its occupants. Weight reduction and high levels of survivability are mutually competing objectives. Therefore, a significant effort must be invested in order to ensure that the vehicle?s survivability is not compromised. Full size blast tests are expensive and time consuming to organize. Using a numerical simulation for predicting the interaction of the blast load with the vehicle and the effects of the explosion to the occupants? safety can minimize the number of such trials, and it will identify the design changes which will increase the survivability of the vehicle and the crew. Such simulation capability must be physics based and able to account for non-centerline explosive threats; the load applied on the vehicle from the blast pressure and the high velocity projectiles (which can be part of the explosive threat); the interaction between the explosive threat, the vehicle, and the occupant; the soil/structure interaction and the gross vehicle response and the effects of blast mitigation material, restraint system, and seat design to the loads developed on the members of an occupant. A Blast Event Simulation sysTem (BEST) has been developed for facilitating the easy use of the LS-DYNA solvers for conducting a complete sequence of explosive simulations. An Anthropometric Test Device (ATD) can also be included in the simulations for assessing loads developed on an occupant during an explosion. The main technical capabilities embedded in the BEST simulation process along with comparisons between simulation results and test data available in the literature are presented in this paper. Details from a validation study associated with the response of a generic structure and a ADT placed inside the structure to the loads from an explosion are also discussed.

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target structure to the loads from the explosion. A major advantage of utilizing the LS-DYNA solvers for blast event simulations instead of CTH is that LS-DYNA is a commercially readily accessible software, has a friendly user interface, it can exchange data with commercial pre and post processors, it is easy to interpret the structure of its data file, and that a numerical models for an ATD can be readily integrated in the simulation as part of the vehicle finite element model.

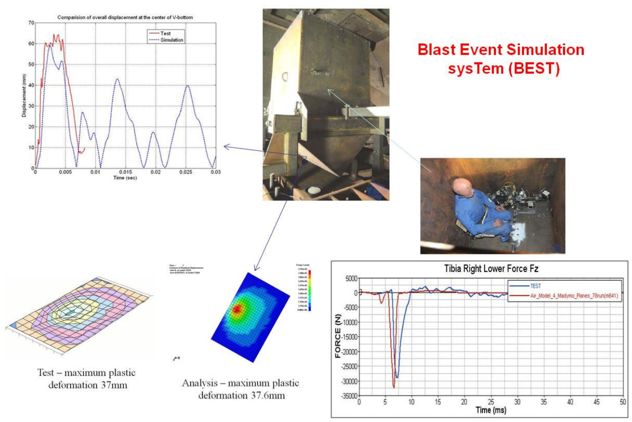


Figure 1. Comparison between results from BEST and test data for a V shaped double bottom structure and the enclosed occupant

The BEST user interface has built-in knowledge for preparing the various data files required for conducting the blast simulation and ADT analysis. In this manner it eliminates the burden of specialized knowledge from the analyst who will be conducting the simulations. BEST provides a series of templates that guide the user in developing the necessary models for the blast event simulations. A capability has been developed for automatically creating the Eulerian finite element model for the air, the soil, and the explosive, given the structural finite element model for the vehicle. An occupant model of an ATD can be introduced inside the vehicle model, if desired. The effect of moisture in the soil properties is considered during the generation of the soil – explosive – air model used by the Eulerian solver. Tracers are defined in the Eulerian model for all structural finite elements which are on the outer part of the vehicle structure and are subjected to the load from the blast. The data for the pressure load from the explosion comprise the loading for the structural response of the target structure. A methodology has also been developed for using the pressure information from the explosion for assigning appropriate velocity and trajectories to projectiles and fragments that are part of the explosive threat. The projectiles are considered along with the blast pressure load to hit the structure and the response of the structure to the combined loads can be computed. In this paper the BEST simulation process is first validated through comparison with test data available in the literature [Bergeron et al, 1998; Williams and McClennan, 2002]. Further validation is presented by analyzing a generic target structure with a V shaped double bottom subjected to a load from an explosion and comparing the results to test data. A Hybrid III ATD is placed inside the structure. A test was conducted for this configuration. Results from the BEST simulation process were compared successfully with test data for the deformation of the structure and for the loads developed in the lower legs of the occupant (Figure 1).

2. FUNCTIONALITY OF BEST

BEST is based on the seamless utilization of the two LS-DYNA solvers (Eulerian and Lagrangian). The capability for creating automatically the solid finite element model for the soil-air-explosive based on the geometry of the target structure is part of the interface. In addition soil models from the literature [Laine and Sandvik, 2001] have been implemented in the interface code to account for the moisture effects in the soil properties. Finally, a capability to include projectiles as part of the explosive and have a target structure hit by both the blast pressure and the projectiles has been developed as part of the interface. Information about the capabilities of the BEST program is summarized in this Section. Figure 2 presents the initial panel of the BEST user interface; each button conducts a separate functionality and an individual panel appears for providing the necessary information associated with the particular functionality. The user can type in the appropriate data and choose between using built-in properties and defining new ones.

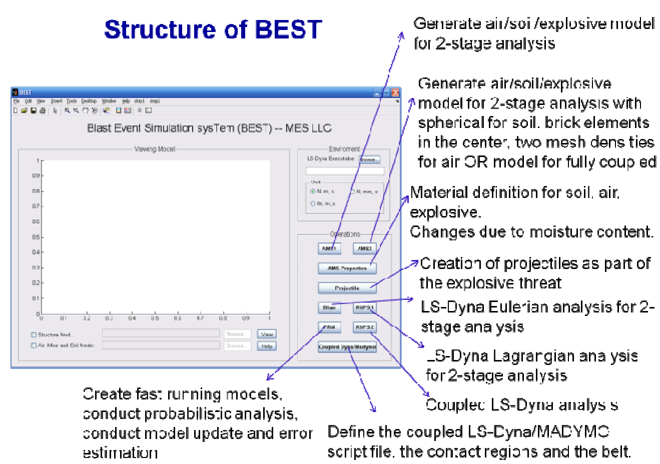


Figure 2. Main functionality of BEST interface

The main steps in the operation of the interface are:
Step 1: Generate the air-explosive-soil model
Step 2: Define the properties for the air-explosive-soil model
Step 3: Define the parameters for the projectiles and generate the appropriate models

Step 4: Calculate the blast pressure using the Eulerian LS-DYNA solver
Step 5: Calculate the response of the vehicle using the Lagrangian LS-DYNA solver and the response of the ADT (if included in the simulation).

During the first step, the structural finite element model of the vehicle structure which will be subjected to the load from the explosion and/or projectiles is provided. A typical such vehicle is presented in Figure 3.

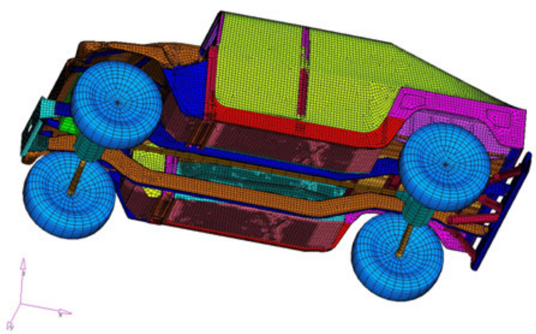


Figure 3. Representative structural finite element model for vehicle utilized in blast event simulations

The shape of the soil-explosive-air computational domain needs to be selected (cylindrical or rectangular), along with the size and the location of the charge, and the desired average element size. Then, BEST generates automatically the solid finite element model for the soil-explosive-air. Multiple layers with different properties can be defined for the soil. The solid finite element model for the air acts like a cast, surrounding the geometry of the vehicle. A representative such model is presented in Figure 4 (it corresponds to the vehicle presented in Figure 3). The appropriate boundary conditions at the boundaries of the air and the soil domains are specified automatically. At the interfaces between the solid air elements and the structural elements tracer points are generated automatically. During the Eulerian solution the pressure time histories at all tracer points are recorded and utilized later for generating the loading on the structure.

Material properties are defined for each layer of the soil model, for the explosive, and for the air sections of the solid model. For the air the following properties must be defined: mass density; cutoff pressure; and dynamic viscosity coefficient. For the explosive the following material properties must be defined: mass density; detonation velocity; and the Chapman-Jouget pressure. In addition the following parameters related to the equation of state must be prescribed: initial internal energy per unit reference volume; initial relative volume; and the constant coefficients. For each layer of soil the following properties are needed: mass density; shear modulus; bulk modulus; constants of the plastic yield function; volumetric strain values; and pressures corresponding to volumetric strain values. BEST has a library of typical property values for the air, soil, and explosive. It also offers the ability to a user to define their own set of properties. The presence of moisture in the soil affects the soil properties. Information from [Laine and Sandvik, 2001] is utilized in this work for propagating the moisture effects to the material properties defined in the LS-DYNA input data file.

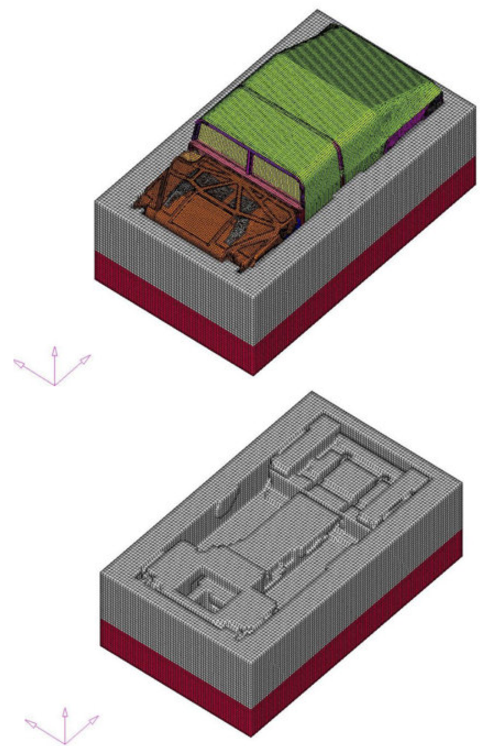
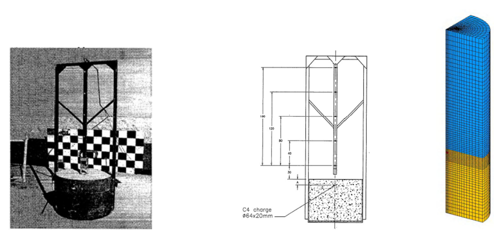


Figure 4. Representative Solid Soil-Explosive-Air model constructed automatically by the interface code

3. CORRELATION TO TEST DATA FOR SMALL BURRIED EXPLOSIVE



(a) (b)

Figure 5. (a) Configuration used in the experiments [Bergeron et al, 1998]; (b) quarter section of simulation model

BEST has been utilized for simulating the experimental set-up presented in Figure 5(a) for which test data are available in [Bergeron et al, 1998]; the corresponding simulation model is presented in Figure 5(b). The various domains (soil (yellow), explosive (red), air(blue)) are presented in the quarter part of the numerical model. The main purpose of this work was to

make certain that BEST simulations can compute correctly the pressure loads from the detonation of a buried explosive. Test data are available in [Bergeron et al, 1998] from gages placed in the air above the ground and from gages placed inside the ground underneath the explosive. The maximum computed pressure is compared to the experimental results for the three gages buried under the charge at distances 8.73 cm, 11.23 cm and 13.73 cm from the bottom of the charge and for two gages placed at 30cm and 70cm above the ground. By comparing the results for the pressures underneath the charge it is ensured that the pressure pulse is modeled correctly through the ground, and by comparing the results for the gages in the air, it is ensured that the pulsation which will apply the load on a potential target is predicted correctly. Three configurations with different depths of burial (DOB) were tested in [Bergeron et al, 1998] with 0cm, 3cm, and 8cm DOB. Simulations were performed for all three configurations. In [Bergeron et al, 1998] each test was conducted 6 times and the results were recorded. A large amount of scattering is present in the test data, thus only a quantitative comparison between experimental results and test data can be made. The same three configurations were also analyzed by BEST using the LS-DYNA Eulerian solver. Tables 1 through 3 summarize the results for the peak pressure at the two gages above the ground.

Position in Air	0cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
30 cm	1971.9	4323	2804	6,228
70 cm	680	1696	1189	1,155

Table 1. Summary of results for gages above the ground for 0cm DOB

Position in Air	3cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
30 cm	414	696	544	748
70 cm	210	468	303	376

Table 2. Summary of results for gages above the ground for 3cm DOB

Position in Air	8cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
30 cm	141	296	191	164
70 cm	64	106	83	84

Table 3. Summary of results for gages above the ground for 8cm DOB

As it can be observed there is significant scattering in the experimental results. The values for the minimum, the maximum, and the average value are presented from the experimental data. The simulation results fall either within the range of the experimental results or very close to the bounds of the experimental results. Similar observation can be made from the summary of similar results presented in Tables 4 through 6 for the three gages buried underneath the charge. Results for all three DOB are presented.

In-Ground Position	0cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
8.73 cm	20,849	68,844	43,349	38,213
11.23 cm	13,100	29,537	21,964	23,041
13.73 cm	12,210	15,961	14,120	9,056

Table 4. Summary of results for gages under the charge for 0cm DOB

In-Ground Position	3cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
8.73 cm	21146.22	54434.11	43650.71	48,300
11.23 cm	11383.24	31426.30	24513.16	28,191
13.73 cm	8770.13	18402.11	14639.87	16,172

Table 5. Summary of results for gages under the charge for 3cm DOB

In-Ground Position	8cm DOB Peak pressure (kPa)			
	Measured			Predicted
	Lowest	Highest	Average	BEST
8.73 cm	53875	56013	54944	57,716
11.23 cm	38217	49519	40743	32,781
13.73 cm	19367	26544	22616	19,355

Table 6. Summary of results for gages under the charge for 8cm DOB

Overall the results demonstrate that the BEST simulation process using standard properties for sand soil provide reasonable correlation with the test data when taking into account the scatter which exists in the test results.

4. CORRELATION TO TEST DATA FOR RESPONSE OF TARGET STRUCTURE FROM BURRIED EXPLOSIVE

The target structure presented in Figure 6 was analyzed with BEST. An aluminum plate of 1.25 in thickness comprises the target. The plate is square with 182.88 cm main dimension along each side. The target

plate is supported at all four corners, and a square box frame is placed on top of the plate. An extra mass of 10,624 kg is placed on top of the frame. A six kilogram C-4 explosive charge is buried under the center of the target plate at a 5cm depth of burial. The test set-up and the test results are discussed in [Williams, K and McClennan, S., 2002]. The numerical models for the target structure and for the soil-explosive-air are presented in Figure 7 (left and right sides, respectively). The permanent deformation induced along the line of symmetry in the target plate is compared between the test results and the BEST simulations (Figure 8). Excellent agreement is observed between them, indicating that BEST can assess correctly the interaction between the explosive, the soil, and the target structure; and that it captures correctly the propagation of the pressure load through the soil and the air, along with its effect on the target structure.

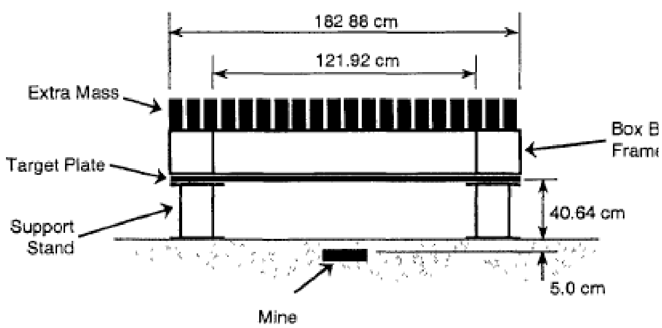


Figure 6. Experimental set-up from [Williams, K and McClennan, S., 2002] of a target structure subject to the load from a buried explosive

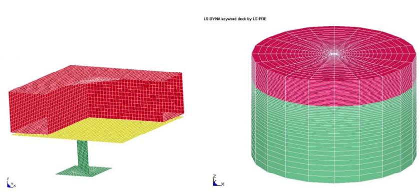


Figure 7. Structural numerical model (quarter model on the left), soil-explosive-air model (on the right)

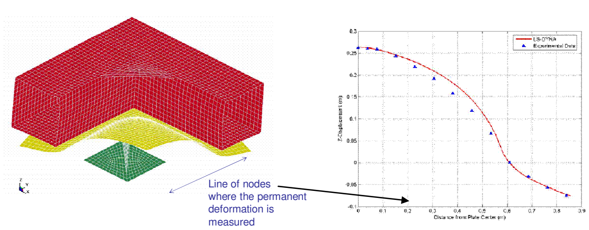


Figure 8. Permanent deformation induced on the target structure and comparison between test results and BEST simulations along a line of symmetry

5. CORRELATION TO TEST DATA FOR GENERIC VEHICLE STRUCTURE AND AN ADT

Technical information related with the generic vehicle structure is presented next. No information was received by any Government organization or any prime vehicle manufacturer in designing the generic vehicle structure and the experimental set up. Figure 9 presents the general engineering drawings for the structure. Armox 370H armor steel with 15mm thickness is used for the entire outer V-shaped bottom structure, while 10mm construction steel is used for the inner bottom and all other panels.

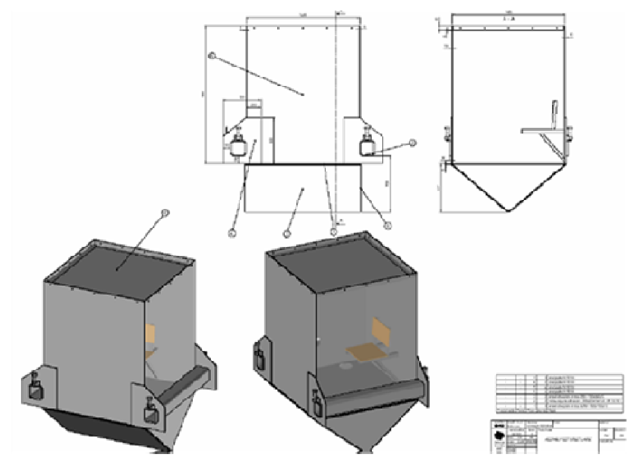


Figure 9. Engineering drawings for generic vehicle structure used in validation study of BEST

The testing was performed at the test banker facility of TNO Defense, Security, and Safety under a contract issued from Michigan Engineering Services, LLC. Figure 10 presents photos of the facility, the generic vehicle, the Hybrid III dummy placed inside the generic vehicle, and a drawing about the test frame structure. The vehicle structure is held rigidly in place through a heavy support frame. The middle photo in Figure 10 zooms in the support assembly that holds the target vehicle structure in place during the explosion. The explosive is placed inside a steel pod underneath the vehicle and directly in the middle of the bottom. This explosive configuration allows concentrating the power released from the explosion to the target structure. 5.51kg of C4 were utilized during the test.

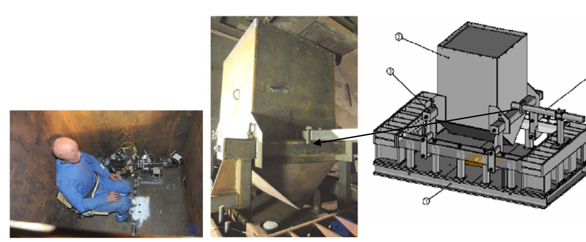


Figure 10. Generic vehicle structure utilized for validating results from BEST simulations

Simulation models developed and utilized by BEST are presented in Figure 11. The combined Eulerian and Langrangian models are presented on the left, while half of the Langrangian structural model is presented in the middle. The Hybrid III simulation model placed inside the generic vehicle is presented on the right side of Figure 11.

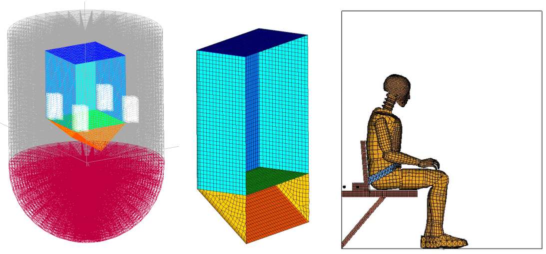


Figure 11. Numerical models used for validating results from BEST simulations

Several comparisons between simulation results and test data were made. The strains were measured at three locations (one out of the four strain gages failed) along the middle of the outer V-shaped bottom. Figure 12 presents the locations of the strain gages and the comparison between test and simulations. Overall good correlation is observed, particularly for the strain gage placed in the middle of the bottom structure, where the highest strain values are encountered. The simulation results cannot capture a large compressive strain which is encountered very early in the test time histories. The measured strains originate from a combination of in-plane compressive deformation and out-of-plane bending deformation. It is assessed that the high compressive strains which appear early in the test results originate from the high speed compressive wave which reaches the strain gages early in the process, while the remaining strains which are captured correctly from the simulations correspond to the bending deformation of the bottom structure.

The displacement time histories in the middle of the inner floor structure and in the middle of the outer V-shaped bottom structure were also measured using high speed cameras. The placement of the cameras and the correlation between simulation results and test is presented in Figure 13. Very good correlation is observed for both the outer bottom structure and the inner floor structure. The high speed camera measuring the displacement on the outer bottom structure failed after the initial part of the measurements, but likely the early stage was recorded when the high response is exhibited. Permanent deformation is induced in the outer bottom structure in both test and simulation, while the inner floor remains within the elastic region in both measurements and simulation. The permanent deformation induced on one of the two sections of the V-shaped outer bottom structure is measured and compared to the simulation results in Figure 14. Since the structure is symmetric and a symmetric explosive was placed at the plane of symmetry, the results are the same for the two sections of the outer bottom structure. Very good correlation is observed for the deformation pattern between the test and the simulations. The comparison for the maximum permanent deformation encountered in the bottom structure is also very good.

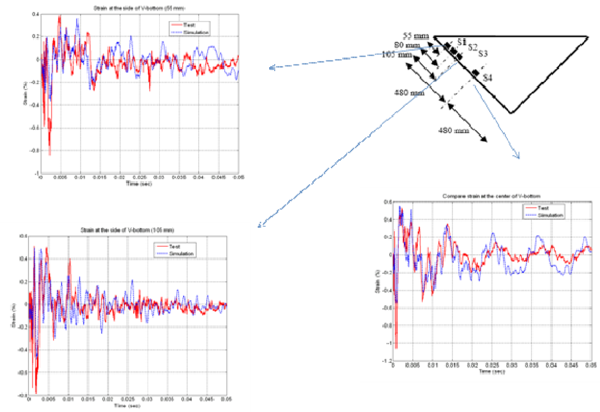


Figure 12. Locations of strain gages on outer V-shaped bottom structure and comparison between test results and BEST simulations

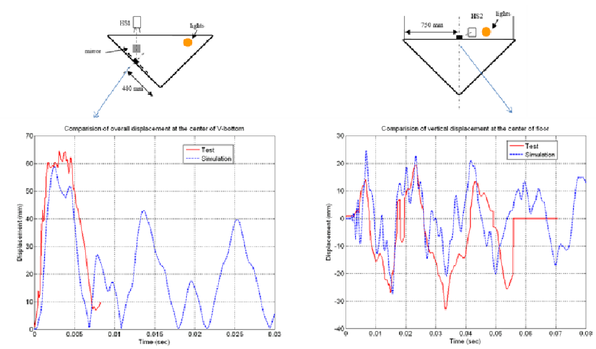


Figure 13. Locations of displacement histories measurements on and outer V-shaped bottom structure (left) and inner floor (right); comparison between test results and BEST simulations

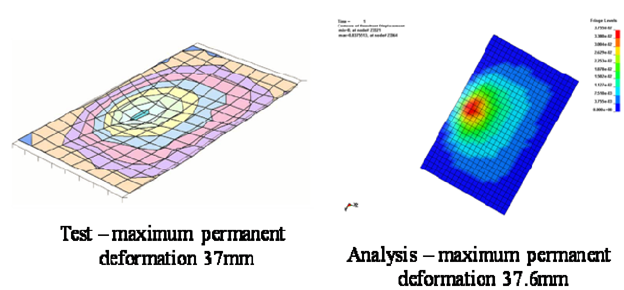


Figure 14. Comparison between test results and BEST simulation of the permanent deformation induced in one of the two sections of the outer V-shaped bottom structure

In the final step of the correlation study, results between test and BEST are compared for the right and the left leg of the occupant. The forces in the vertical z-

direction and in the forward/back x-direction at the lower and upper tibia of the right and the left legs are compared with measurements. Results for the right leg are presented in Figure 15, while results for the left leg are presented in Figure 16 (for the left leg the measurements failed for the upper tibia). Good correlation is observed in capturing the maximum forces which are developed in the lower extremities of the occupant. It is worth mentioning that all existing ATD models have been developed for automotive crash testing, thus, the embedded measurement capabilities and the corresponding simulation models have been geared towards operating properly in the time scales encountered in automotive crashes. The time scales encountered in explosive events are of much shorter duration and this must be considered when comparing measurements and simulations. Therefore, it is also useful to further compare the kinematic behavior of the ATDs between test and simulation in addition to the absolute values of the forces. Such comparison between the BEST results and the recorded motion from test is presented in Figure 17. The good correlation which is observed in Figure 17 further demonstrates the feasibility of using BEST simulation technology for modeling the response of a vehicle's occupant to a blast.

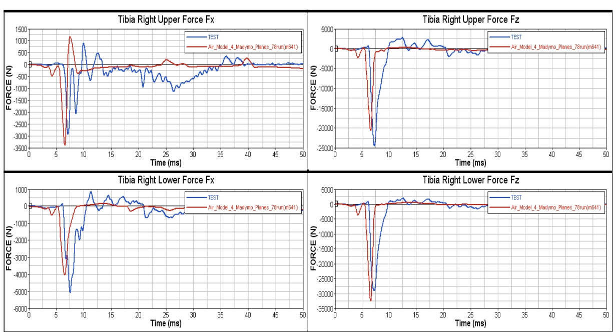


Figure 15. Comparison between BEST results and test data for the forces developed on the right tibia

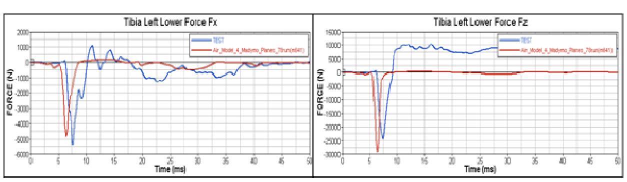


Figure 16. Comparison between BEST results and test data for the forces developed on the left leg

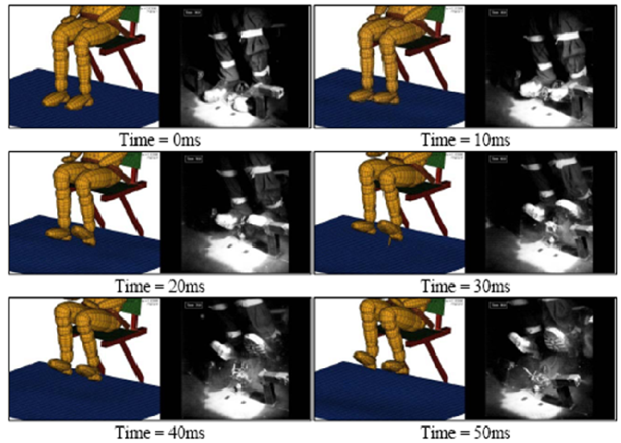


Figure 17. Comparison of the kinematic response of the ATD between BEST simulations and test for various time instances

6. CONCLUSIONS

In this paper, an approach for simulating blast simulation events is presented and validated. It is based on utilizing readily available computational methods and combining them to simulate the explosion of a buried explosive charge, the propagation of the shock wave through the soil and the air, the load from the shock wave on a target structure, and the response of the structure to the shock load. Since the ultimate objective is to design a vehicle with the safety of the occupants in mind, an ADT finite element model can be included as part of the vehicle finite element model in the simulations. Based on comparisons with test data, an ADT model can capture well the loads developed in the legs of an occupant during an explosion. In the future, the BEST simulation process will be used for determining the impact of design changes in the vehicle structure and of the utilization of blast mitigation strategies to the safety of the occupants.

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